FINAL REPORT

Subject Development of two-axial bow-tie atom trap with near-field light

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Abstract We developed a cross-shaped structure with a multilayer film for the 3D atom trap. The spatial profile of near-field light produced in the center gap was obtained from the finite difference time domain simulations, and the trap potential for a single Rb atom was also calculated. Based on the results, we determined the angle of slope, the radius of curvature of edges in the center, the thickness of each layer, and the size of the trap space. In keeping with the design, the cross-shaped structure with the trap space of 400 nm × 140 nm was fabricated through dry-etching process including focused-ion-beam milling and gold sputtering. The depth of the trap potential was estimated to exceed 10 μK in terms of temperature, which is easily obtained by using the standard laser-cooling techniques, from the approximate calculations with the WKB method. In addition, we evaluated the trapping time of the cold Rb atom to be over 20 seconds from numerical estimations of trap loss processes involving tunneling of the thin potential barrier and collision with background gaseous atoms.

1. Goal

Nanophotonics has a potential to lead to tremendous breakthrough in nano-scale science. Indeed, the near-field light technology allows the optical storage far beyond 1 Tb/in^2 in combination with magnetic recording. In future, they say that the data capacity of 1 Pbyte is required, which is comparable to the human brain. In this case, the control precision exceeds 1 nm and will be atomic scale. Accordingly, it is very important to study the interaction mechanism of atoms and near-field light for development of the ubiquitous system by nanophotonics. Moreover, development of quantum functional devices is also one of the most important subjects. Atoms have definitely discrete energy levels, so that the atomic system is more reliable than one using quantum-dots with respect to the signal transmission. However, it is not easy to fix the atomic position for long time on a substrate of optoelectric circuits. To investigate the near-field interaction and functionalize the atom element, we develop the nanophotonic device for 3D confinement of individual atoms with near-field light.

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14. ABSTRACT
This is a report on the development of a cross-shaped structure with a multilayer film for a 3D atom trap.

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2. Principle of 3D atom confinement

Since near-field light rapidly decays in a Yukawa-function manner, it affects a strong dipole force on atoms near resonance. When the light frequency is detuned slightly above from the atomic resonant frequency, namely, blue-detuned, the dipole force is repulsive. Figure 1 schematically shows the trapping structure of a single atom with near-field lights. Each near-field light (NFL) arranged at each lattice point of the unit pushes the atom and confines it in the center under blue-detuning conditions.

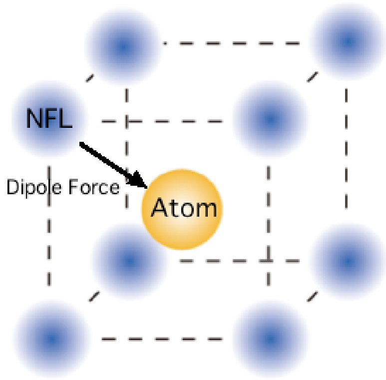
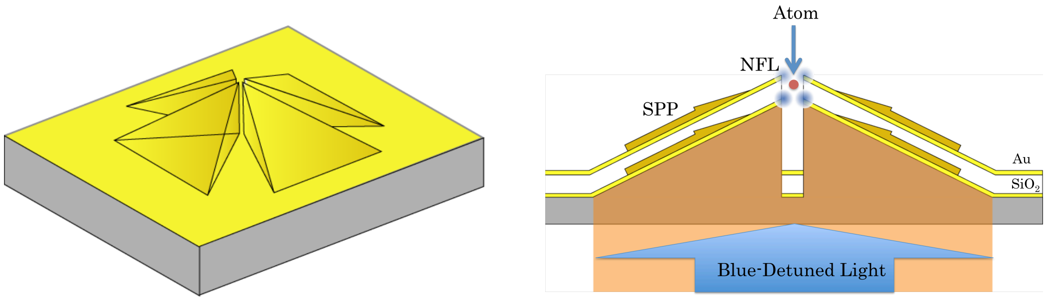


Fig. 1 Near-field-light lattice working as a 3D atom trap.

3. Design of cross-shaped structure

In order to realize the near-field-light lattice, we designed the multilayered cross-shaped structure shown in Fig. 2. We developed a two-axial bow-tie structure into the cross-shaped structure adapting to the fabrication process with etching. Figure 2(b) shows the cross section. The Au-SiO_2-Au layers are produced on the slope. When illuminating the bottom surface with a blue-detuned laser beam, surface plasmon-polariton (SPP) is induced and propagates along the slope, and then near-field lights are produced at each border between Au and SiO_2 layers. An atom cooled down to 10 μK with the magneto optical trap (MOT), which is the standard method of laser cooling of neutral atoms, is plugged into the center space by applying a weak boost laser beam.



(a) (b)

Fig.2 (a) Sketch of cross structure, and (b) the cross section.

Near-field light strong enough for trapping the laser-cooled atom can be induced thanks to the electric field enhancement effect at metal tips. The intensity of near-field light depends on the thickness of each layer. It is required as the trap condition that the upper near-field light is weaker than the lower near-field light. In order to determine the layer thickness, we conducted the finite difference time domain (FDTD) simulations in the case of the wavelength of 780 nm for the Rb atom confinement and examined the intensity distribution of near-field light, changing each layer thickness. Figure 3 shows a result. The thicknesses satisfying the trap condition were less than 40 nm for the inner Au layer, more than 26 nm for the outer Au layer, and more than 80 nm for the intermediate SiO_2 layer. On the other hand, we found that the slope angle and the taper angle were 60 degree and 90 degree, respectively.

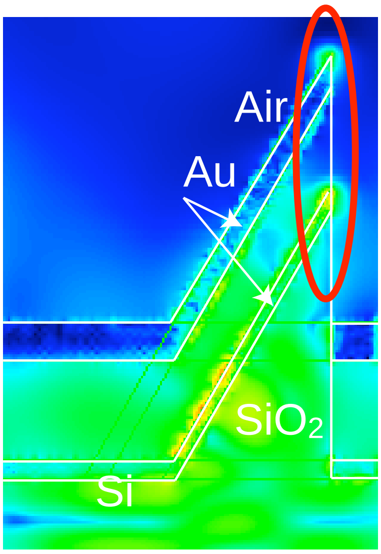


Fig. 3 Intensity distribution of near-field light obtaine from FDTD simulations

When the Rb atom is cooled down to 10 μK, the de Broglie wavelength is 60 nm. Then, the radius of curvature of the edge, which almost equals the decay length of near-field light, must be larger than 60 nm. And calculating the trap potential, we estimated that the lateral length and the vertical length of the center trap space were less than 6.5-fold and 4-fold of the radius of curvature, respectively.

4. Fabrication of cross-shaped structure

We fabricated the cross-shaped structure by processing a silicon-on-insulator (SOI) wafer with dry etching, focused ion beam (FIB) milling, and sputtering. Figure 4 shows the process of a single bow-tie structure: (a) the SOI wafer is composed of Si-SiO_2-Si layers, (b) it was anodically-bounded on a Pyrex glass, (c) the upper Si layer was removed by etching with a TMAH+CH_3COOH+HNO_3+HF solution, (d) the SiO_2 film was etched with a BHF solution,

(e) a resist mask was patterned on the SiO_2 film with ZEP520A, the dry etching processing was conducted (f) with CF_4 and then (g) with Cl_2+Ar, (h) a bow-tie structure was formed by the FIB milling, and finally the Au-SiO_2-Au layers were made in series by (i) Au, (j) SiO_2 , (k) Au sputtering.

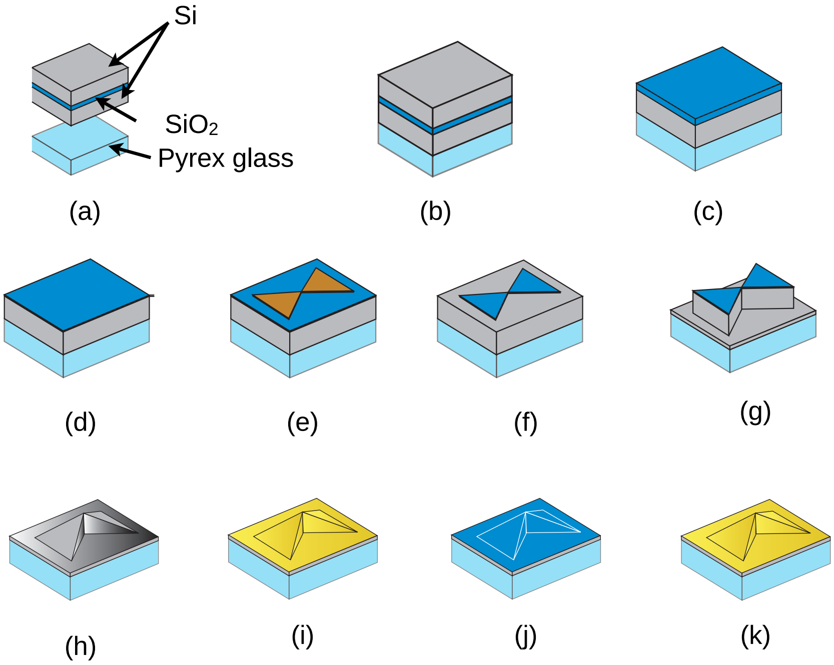
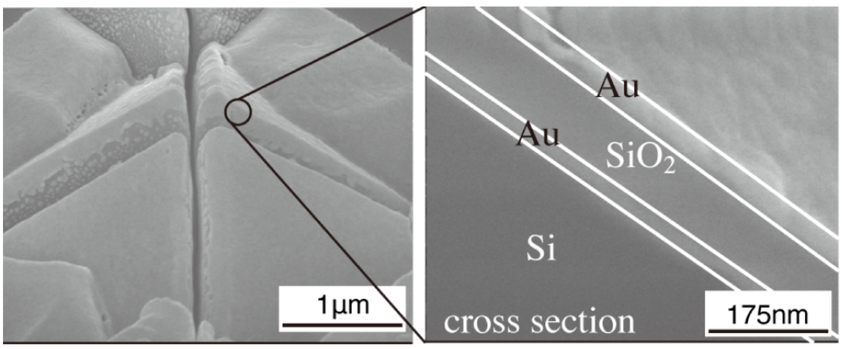


Fig. 4 Fabrication process of a single bow-tie.

Similarly to the single-axial fabrication, we made a cross-shaped two-axial bow-tie structure. Figure 5 shows the SEM images. The slope length is 1.3 μm and the slope angle is 60 degree, while the taper angle is 90 degree. From the top view shown in Fig. 5(a), the radius of curvature of the top edge was estimated to be 100 nm, and the center space was estimated to be 400 nm in the lateral direction and 140 nm in the vertical direction. From Fig. 5(b) magnifying the multiple layers, the thicknesses of the outer and inner Au layers were respectively estimated to be 40 nm and 26 nm, and the SiO_2 layer was estimated at 100 nm.



(a) (b)

Fig. 5 SEM images of the cross-shaped structure.

5. Numerical estimation of trap potential

In order to show the feasibility of trapping a ^{87}Rb atom, we calculated the trap potential V(r) made up of the repulsive dipole-force potential and the cavity potential, where it comes from the van der Waals force. Figure 6 shows an example obtained by considering our experimental conditions. The horizontal lines show the quantized vibration energy levels E_n obtained from the WKB quantized condition

$$2\int_b^a \sqrt{2m\{E_n - V(r)\}}\,dr = \left(n + \frac{1}{2}\right)h \text{ , n=0, 1, 2, … ,}$$

where a and b are the classical turning points, m is the atomic mass, and h is the Planck constant. The lowest level E_0 in the zero-point vibration is about 10 μK in terms of temperature measured from the bottom of the trap potential. The cold atoms below the temperature can be easily generated by MOT. Since the similar trap potentials are produced in the x, y, and z-axes, we can confine the cold ^{87}Rb atom three dimensionally in this configuration.

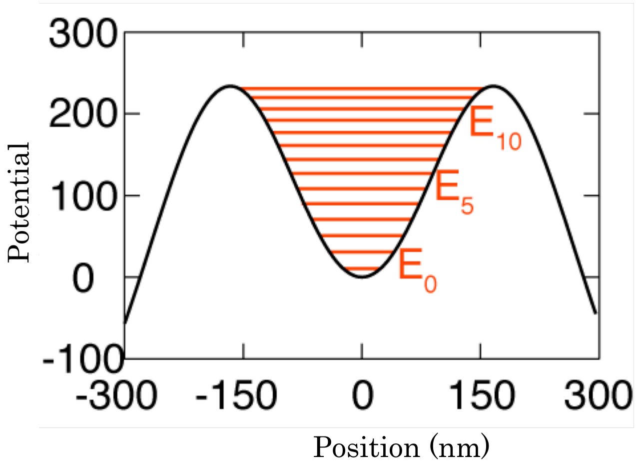


Fig. 6 Quantized motion of a trapped ^{87}Rb atom.

6. Retention time

The trapped atom escapes from the trap due to some factors. The serious loss mechanisms are tunneling of the potential barrier and collision with residual background gaseous atoms. The tunneling possibility is written as

$$P_t \approx \exp\left[-\frac{2}{\hbar}\int_a^b \sqrt{2m\{V(r) - E_n\}}\,dr\right]$$

with the WKB method. In the case where the atom faces N times with the right and left walls as shown in Fig. 6, the tunneling time is approximately given by

$$\tau_t \approx 2N\int \frac{dr}{v(r)} \text{ ,}$$

where v(r) is the position-dependent atomic velocity. Assuming that the atom remains in the potential well until the probability density is 0.5, the number N is obtained from

$$\left[\left(1-P_t^L\right)\left(1-P_t^R\right)\right]^N = 0.5 \ ,$$

where P_t^L and P_t^R are the tunneling possibilities for the left-hand side potential barrier and for the right-hand side potential barrier, respectively. Figure 7 shows the tunneling time for ^{87}Rb plotted as a function of the potential depth. As the potential is deeper, the holding time of the trapped atom exponentially increases.

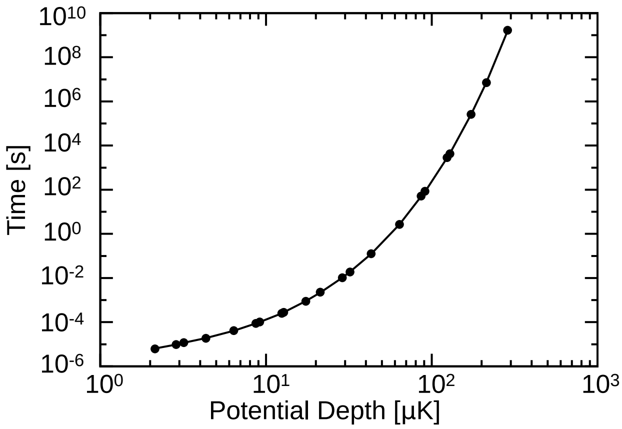


Fig. 7 Tunneling time plotted as a function of the potential depth.

Under ultra high vacuum of 10^{-9} Pa, the time required for loss from the trap by collisions with the background gas is estimated to be about 20 seconds. Figure 8 shows the retention time of ^{87}Rb as a function of the potential depth. The collision loss dominates in the region where the potential is large, while the tunneling loss dominates in the region where the potential is small. This comes from the fact that the atom goes through the potential barrier when the width and height are thin and low. When the blue detuning of the light frequency is 10^4 GHz and the intensity of the near-field light produced in the trap space is 7×10^5 mW/cm^2, the potential depth is 124 μK. In this case, the retention time of ^{87}Rb is estimated to be 21 seconds.

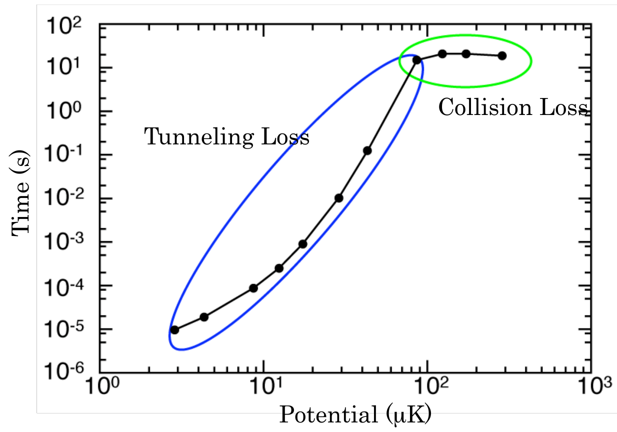


Fig. 8 Retention time plotted as a function of the potential depth.

7. Conclusions

The cross-shaped structure can be used for 3D trapping of a single neutral atom. Blue-detuned near-field lights confine a cold Rb atom with 10 mK for a long time of over 20 seconds in the space of 400 nm×400 nm×140 nm. The tunneling of the potential barrier is dominant as the loss mechanism. The two-axial bow-tie trap will be applied to a single-photon gate operating by quantum jump. It is possible to make additional multiple layers. For example, the Au-SiO_2-Au-SiO_2-Au layers lead to trapping of two single atoms. Such a device will be used as a qubit composed of two atoms for quantum computation.

Original Paper

Now in preparation**.**

Presentation in Conference

[1] M. Natumeda, Y. Mizuochi, H. Ito, “Fabrication of multilayer cross-shaped structures and numerical estimation of trapping time of atoms in thestructures with near-field light,” Annual meeting of the Japan Society of Applied Physdics, 2008.

[2] Y. Mizuochi, M. Natumeda, H. Ito, “3D confinement of an atom using near-field light in a cross-shaped bow-tie structure with multi layers,” Annual meeting of the Japan Society of Applied Physdics, 2008.